Docket No. UVD 0298 PA

CLAIMS

1. A system for actively damping boom noise comprising:

an enclosure defining a plurality of low-frequency acoustic modes;

an acoustic wave sensor;

a motion sensor secured to a panel of said enclosure;

an acoustic wave actuator substantially collocated with said acoustic wave sensor;

a first electronic feedback loop defining an acoustic damping controller; and

a second electronic feedback loop defining a vibro-acoustic controller.

2. A system for actively damping boom noise as claimed in claim 1 wherein said plurality of low-frequency acoustic modes comprise modes selected from cavity induced low-frequency acoustic modes, structural vibration induced low-frequency acoustic modes, low-frequency acoustic modes excited by idle engine firings, and combinations thereof.

3. A system for actively damping boom noise as claimed in claim 1 wherein said motion sensor comprises an accelerometer.

4. A system for actively damping boom noise as claimed in claim 1 wherein said motion sensor is configured to produce a motion sensor signal representative of at least one of said plurality of low-frequency acoustic modes.

5. A system for actively damping boom noise as claimed in claim 4 wherein said motion sensor signal comprises an electric signal indicative of measured acceleration detected by said motion sensor as a result of structural vibration of said panel.

6. A system for actively damping boom noise as claimed in claim 4 wherein said motion sensor signal is representative of a single structural vibration induced low-frequency acoustic mode.

7. A system for actively damping boom noise as claimed in claim 4 wherein said motion sensor signal is representative of a plurality of structural vibration induced low-frequency acoustic modes.

8. A system for actively damping boom noise as claimed in claim 1 wherein said enclosure further defines a middle roof panel and a rear roof panel.

9. A system for actively damping boom noise as claimed in claim 8 wherein a middle panel motion sensor is secured to said middle roof panel and a rear panel motion sensor is secured to said rear roof panel.

10. A system for actively damping boom noise as claimed in claim 9 wherein said middle panel motion sensor comprises an accelerometer and said rear panel motion sensor comprises an accelerometer.

11. A system for actively damping boom noise as claimed in claim 9 wherein said middle panel motion sensor is configured to produce a middle panel motion sensor signal representative of at least one of said plurality of low-frequency acoustic modes and wherein said rear panel motion sensor is configured to produce a rear panel motion sensor signal representative of at least one of said plurality of low-frequency acoustic modes.

12. A system for actively damping boom noise as claimed in claim 11 wherein said middle panel motion sensor signal comprises an electric signal indicative of measured acceleration detected by said middle panel motion sensor as a result of structural vibration of said middle roof panel and wherein said rear panel motion sensor signal

comprises an electric signal indicative of measured acceleration detected by said rear panel motion sensor as a result of structural vibration of said rear roof panel.

13. A system for actively damping boom noise as claimed in claim 11 wherein said middle panel motion sensor signal is representative of a single roof structural vibration induced low-frequency acoustic mode and said rear panel motion sensor signal is representative of a single roof structural vibration induced low-frequency acoustic mode.

14. A system for actively damping boom noise as claimed in claim 13 wherein said middle panel motion sensor signal and said rear panel motion sensor signal are representative of the same roof structural vibration induced low-frequency acoustic mode.

15. A system for actively damping boom noise as claimed in claim 13 wherein said middle panel motion sensor signal and said rear panel motion sensor signal are representative of different roof structural vibration induced low-frequency acoustic modes.

16. A system for actively damping boom noise as claimed in claim 11 wherein said middle panel motion sensor signal is representative of a plurality of roof structural vibration induced low-frequency acoustic modes and said rear panel motion sensor signal is representative of a plurality of roof structural vibration induced low-frequency acoustic modes.

17. A system for actively damping boom noise as claimed in claim 1 wherein said acoustic wave sensor comprises a microphone.

18. A system for actively damping boom noise as claimed in claim 1 wherein said acoustic wave sensor is positioned within said enclosure.

19. A system for actively damping boom noise as claimed in claim 1 wherein said acoustic wave sensor is configured to produce an acoustic wave sensor signal representative of at least one of said plurality of low-frequency acoustic modes.

20. A system for actively damping boom noise as claimed in claim 19 wherein said acoustic wave sensor signal comprises an electric signal indicative of measured acoustic resonance detected by said acoustic wave sensor within said enclosure.

21. A system for actively damping boom noise as claimed in claim 19 wherein said acoustic wave sensor signal is representative of a single cavity induced low-frequency acoustic mode.

22. A system for actively damping boom noise as claimed in claim 19 wherein said acoustic wave sensor signal is representative of a plurality of cavity induced low-frequency acoustic modes.

23. A system for actively damping boom noise as claimed in claim 1 wherein said acoustic damping controller defines a first electronic feedback loop input coupled to an acoustic wave sensor signal and a first electronic feedback loop output, wherein said first electronic feedback loop is configured to generate a first electronic feedback loop output signal by applying a feedback loop transfer function to said acoustic wave sensor signal.

24. A system for actively damping boom noise as claimed in claim 1 wherein said vibro-acoustic controller defines a second electronic feedback loop input coupled to a motion sensor signal and a second electronic feedback loop output, wherein said second electronic feedback loop is configured to generate a second electronic feedback loop output signal by applying a feedback loop transfer function to said motion sensor signal.

25. A system for actively damping boom noise as claimed in claim 1 wherein said second electronic feedback loop further defines a middle panel vibro-acoustic controller in parallel with a rear panel vibro-acoustic controller.

26. A system for actively damping boom noise as claimed in claim 25 wherein said middle panel vibro-acoustic controller defines a middle panel vibro-acoustic controller input coupled to a middle panel motion sensor signal and a middle panel vibro-acoustic controller output, wherein said middle panel vibro-acoustic controller is configured to generate a middle panel vibro-acoustic controller output signal by applying a feedback loop transfer function to said middle panel motion sensor signal.

27. A system for actively damping boom noise as claimed in claim 25 wherein said rear panel vibro-acoustic controller defines a rear panel vibro-acoustic controller input coupled to a rear panel motion sensor signal and a rear panel vibro-acoustic controller output, wherein said rear panel vibro-acoustic controller is configured to generate a rear panel vibro-acoustic controller output signal by applying an electronic feedback loop transfer function to said rear panel motion sensor signal.

28. A system for actively damping boom noise as claimed in claim 25 wherein a middle panel vibro-acoustic controller output signal and a rear panel vibro-acoustic controller output signal are combined to generate a second electronic feedback loop output signal.

29. A system for actively damping boom noise as claimed in claim 1 wherein said acoustic wave actuator substantially collocated with said acoustic wave sensor is positioned within said enclosure and wherein said acoustic wave actuator is responsive to a first electronic feedback loop output signal and a second electronic feedback loop output signal.

30. A system for actively damping boom noise as claimed in claim 1 wherein said acoustic wave actuator substantially collocated with said acoustic wave sensor are positioned to correspond to the location of the acoustic anti-node of a target acoustic mode within said enclosure.

31. A system for actively damping boom noise as claimed in claim 1 wherein said acoustic wave actuator introduces characteristic acoustic dynamics into said system and wherein said first and second electronic feedback loops are configured to introduce inverse acoustic dynamics into said system.

32. A system for actively damping boom noise as claimed in claim 29 wherein said first and second electronic feedback loop output signals are representative of a rate of change of volume velocity to be produced by said acoustic wave actuator.

33. A system for actively damping boom noise as claimed in claim 1 wherein said enclosure comprises a cabin of an automobile.

34. A system for actively damping boom noise comprising:

an enclosure defining a plurality of low-frequency acoustic modes;

an acoustic wave sensor positioned within said enclosure,

wherein said acoustic wave sensor is configured to produce an acoustic wave sensor signal representative of at least one of said plurality of low-frequency acoustic modes;

a motion sensor secured to a panel of said enclosure,

wherein said motion sensor is configured to produce a motion sensor signal representative of at least one of said plurality of low-frequency acoustic modes;

an acoustic wave actuator substantially collocated with said acoustic wave sensor and positioned within said enclosure,

wherein said acoustic wave actuator is responsive to a first electronic feedback loop output signal and a second electronic feedback loop output signal;

a first electronic feedback loop defining an acoustic damping controller,

wherein said acoustic damping controller defines a first electronic feedback loop input coupled to said acoustic wave sensor signal and a first electronic feedback loop output,

wherein said first electronic feedback loop is configured to generate said first electronic feedback loop output signal by applying a feedback loop transfer function to said acoustic wave sensor signal,

wherein said feedback loop transfer function comprises a second order differential equation including a first variable representing a predetermined damping ratio and a second variable representing a tuned natural frequency,

said second variable representing said tuned natural frequency is selected to be tuned to a natural frequency of at least one of said plurality of low-frequency acoustic modes,

said feedback loop transfer function defines a frequency response having a characteristic maximum gain substantially corresponding to the value of said tuned natural frequency,

wherein said feedback loop transfer function creates a 90 degree phase lead substantially at said tuned natural frequency; and

a second electronic feedback loop defining a vibro-acoustic controller,

wherein said vibro-acoustic controller defines a second electronic feedback loop input coupled to said motion sensor signal and a second electronic feedback loop output, and

wherein said second electronic feedback loop is configured to generate said second electronic feedback loop output signal by applying said feedback loop transfer function to said motion sensor signal.

35. A system for actively damping boom noise as claimed in claim 34 wherein said motion sensor signal comprises an electric signal indicative of measured acceleration detected by said motion sensor as a result of structural vibration of said panel, said acoustic wave sensor signal comprises an electric signal indicative of measured resonance detected by said acoustic wave sensor within said enclosure, and said first and second electronic feedback loop output signals are representative of a rate of change of volume velocity to be produced by said acoustic wave actuator.

36. A system for actively damping boom noise as claimed in claim 34 wherein said motion sensor signal comprises an electric signal indicative of measured acceleration detected by said motion sensor as a result of structural vibration of said panel, said acoustic wave sensor signal comprises an electric signal indicative of measured resonance detected by said acoustic wave sensor within said enclosure, and said first and second electronic feedback loop output signals are representative of a rate of change of volume velocity to be produced by said acoustic wave actuator, and wherein said feedback loop transfer function is as follows:

$$\frac{V(s)}{P(s)} = C\frac{s^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad (1)$$

where the units of $V(s)$ corresponds to said rate of change of volume velocity, $P(s)$ corresponds to the pressure at the location of said acoustic wave actuator and said acoustic wave sensor, s is a Laplace variable, ζ is a damping ratio, ω_n is said

tuned natural frequency, and C is a constant representing at least one of a power amplification factor and a gain value.

37. A system for actively damping boom noise as claimed in claim 34 wherein said motion sensor signal comprises an electric signal indicative of measured acceleration detected by said motion sensor as a result of structural vibration of said panel, said acoustic wave sensor signal comprises an electric signal indicative of measured resonance detected by said acoustic wave sensor within said enclosure, and said first and second electronic feedback loop output signals are representative of a rate of change of volume velocity to be produced by said acoustic wave actuator, and wherein said feedback loop transfer function is as follows:

$$\frac{V(s)}{P(s)} = -C\frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad (2)$$

where the units of $V(s)$ corresponds to said rate of change of volume velocity, $P(s)$ corresponds to the pressure at the location of said acoustic wave actuator and said acoustic wave sensor, s is a Laplace variable, ζ is a damping ratio, ω_n is said tuned natural frequency, and C is a constant representing at least one of a power amplification factor and a gain value.

38. A system for actively damping boom noise as claimed in claim 34 wherein said motion sensor signal comprises an electric signal indicative of measured acceleration detected by said motion sensor as a result of structural vibration of said panel, said acoustic wave sensor signal comprises an electric signal indicative of measured resonance detected by said acoustic wave sensor within said enclosure, and said first and second electronic feedback loop output signals are representative of a rate of change of volume velocity to be produced by said acoustic wave actuator, and wherein

said feedback loop transfer function is as follows:

$$\frac{V(s)}{P(s)} = C\frac{s^2 + 2\zeta_s \omega_{ns} s + \omega_{ns}^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad (3)$$

where the units of $V(s)$ corresponds to said rate of change of volume velocity, $P(s)$ corresponds to the pressure at the location of said acoustic wave actuator and said acoustic wave sensor, s is a Laplace variable, ζ and ζ_s are damping ratios, ω_n and ω_{ns} are said tuned natural frequencies, and C is a constant representing at least one of a power amplification factor and a gain value.

39. A system for actively damping boom noise as claimed in claim 34 wherein said motion sensor signal comprises an electric signal indicative of measured acceleration detected by said motion sensor as a result of structural vibration of said panel, said acoustic wave sensor signal comprises an electric signal indicative of measured resonance detected by said acoustic wave sensor within said enclosure, and said first and second electronic feedback loop output signals are representative of a rate of change of volume velocity to be produced by said acoustic wave actuator, and wherein said feedback loop transfer function is as follows:

$$\frac{V(s)}{P(s)} = C\frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad (4)$$

where the units of $V(s)$ corresponds to said rate of change of volume velocity, $P(s)$ corresponds to the pressure at the location of said acoustic wave actuator and said acoustic wave sensor, s is a Laplace variable, ζ is a damping ratio, ω_n is said tuned natural frequency, and C is a constant representing at least one of a power amplification factor and a gain value.

40. A method for actively damping boom noise within an enclosure defining a plurality of low-frequency acoustic modes comprising the steps of:

securing a motion sensor to a panel of said enclosure, wherein said motion sensor is configured to produce a motion sensor signal representative of at least one of said plurality of low-frequency acoustic modes;

positioning an acoustic wave sensor within said enclosure, wherein said acoustic wave sensor is configured to produce an acoustic wave sensor signal representative of at least one of said plurality of low-frequency acoustic modes;

positioning an acoustic wave actuator responsive to a first electronic feedback loop output signal and a second electronic feedback loop output signal within said enclosure, wherein said acoustic wave actuator is substantially collocated with said acoustic wave sensor;

coupling a first electronic feedback loop input of a first electronic feedback loop to said acoustic wave sensor signal and a first electronic feedback loop output, wherein

said first electronic feedback loop is configured to generate said first electronic feedback loop output signal by applying a feedback loop transfer function to said acoustic wave sensor signal;

coupling a second electronic feedback loop input of a second electronic feedback loop to said motion sensor signal and a second electronic feedback loop output, wherein

said second electronic feedback loop is configured to generate said second electronic feedback loop output signal by applying a feedback loop transfer function to said motion sensor signal; and

operating said acoustic wave actuator in response to said first and second electronic feedback loop output signals.

41. A method for actively damping boom noise within an enclosure defining a plurality of low-frequency acoustic modes comprising the steps of:

securing a motion sensor to a panel of said enclosure, wherein said motion sensor is configured to produce a motion sensor signal representative of at least one of said plurality of low-frequency acoustic modes;

positioning an acoustic wave sensor within said enclosure, wherein said acoustic wave sensor is configured to produce an acoustic wave sensor signal representative of at least one of said plurality of low-frequency acoustic modes;

positioning an acoustic wave actuator responsive to a first electronic feedback loop output signal and a second electronic feedback loop output signal within said enclosure, wherein said acoustic wave actuator is substantially collocated with said acoustic wave sensor;

coupling a first electronic feedback loop input of a first electronic feedback loop to said acoustic wave sensor signal and a first electronic feedback loop output, wherein

said first electronic feedback loop is configured to generate said first electronic feedback loop output signal by applying a feedback loop transfer function to said acoustic wave sensor signal,

wherein said feedback loop transfer function comprises a second order differential equation including a first variable representing a predetermined damping ratio and a second variable representing a tuned natural frequency,

said second variable representing said tuned natural frequency is selected to be tuned to a natural frequency of at least one of said plurality of low-frequency acoustic modes,

said feedback loop transfer function defines a frequency response having a characteristic maximum gain substantially corresponding to the value of said tuned natural frequency, and

wherein said feedback loop transfer function creates a 90 degree phase lead substantially at said tuned natural frequency;

coupling a second electronic feedback loop input of a second electronic feedback loop to said motion sensor signal and a second electronic feedback loop output, wherein

said second electronic feedback loop is configured to generate said second electronic feedback loop output signal by applying said feedback loop transfer function to said motion sensor signal;

selecting a value for said first variable representing said predetermined damping ratio;

selecting a value for said second variable representing said tuned natural frequency; and

operating said acoustic wave actuator in response to said first and second electronic feedback loop output signals.

42. A system for actively damping boom noise comprising an enclosure defining at least one tailgate vibration induced low-frequency acoustic mode, a first cavity induced low-frequency acoustic mode, and a roof structural vibration induced low-frequency acoustic mode, and wherein the resonant frequency of said at least one tailgate vibration induced low-frequency acoustic mode is substantially different than the resonant frequencies of said first cavity induced low-frequency acoustic mode or said roof structural vibration induced low-frequency acoustic mode.

43. A system for actively damping boom noise as claimed in claim 42 wherein the resonant frequency of said at least one tailgate vibration induced low-frequency acoustic mode is about 30 Hz.

44. A system for actively damping boom noise as claimed in claim 42 wherein the resonant frequency of said first cavity induced low-frequency acoustic mode is about 45 Hz.

45. A system for actively damping boom noise as claimed in claim 42 wherein the resonant frequency of said roof structural vibration induced low-frequency acoustic mode is about 40 Hz.

46. A system for actively damping boom noise comprising:

an enclosure defining a tailgate panel and at least one tailgate vibration induced low-frequency acoustic mode;

a sensor;

an acoustic wave actuator; and

an electronic feedback loop.

47. A system for actively damping boom noise as claimed in claim 46 wherein said sensor is selected from the group consisting of an acoustic wave sensor, a motion sensor, and a combination thereof.

48. A system for actively damping boom noise as claimed in claim 47 wherein said motion sensor is secured to said tailgate panel of said enclosure.

49. A system for actively damping boom noise as claimed in claim 47 wherein said sensor is said acoustic wave sensor and said acoustic wave actuator is substantially collocated with said acoustic wave sensor.

50. A system for actively damping boom noise as claimed in claim 46 wherein said electronic feedback loop is selected from the group consisting of a first electronic feedback loop defining an acoustic damping controller, a second electronic feedback loop defining a vibro-acoustic controller, and a combination thereof.

51. A system for actively damping boom noise as claimed in claim 47 wherein said motion sensor comprises an accelerometer.

52. A system for actively damping boom noise as claimed in claim 47 wherein said motion sensor is configured to produce a tailgate motion sensor signal representative of said at least one tailgate vibration induced low-frequency acoustic mode.

53. A system for actively damping boom noise as claimed in claim 52 wherein said tailgate motion sensor signal comprises an electric signal indicative of measured acceleration detected by said motion sensor as a result of structural vibration of said tailgate panel.

54. A system for actively damping boom noise as claimed in claim 52 wherein said tailgate motion sensor signal is representative of a single tailgate vibration induced low-frequency acoustic mode.

55. A system for actively damping boom noise as claimed in claim 52 wherein said tailgate motion sensor signal is representative of a plurality of tailgate vibration induced low-frequency acoustic modes.

56. A system for actively damping boom noise as claimed in claim 47 wherein said acoustic wave sensor comprises a microphone.

57. A system for actively damping boom noise as claimed in claim 47 wherein said acoustic wave sensor is positioned within said enclosure.

58. A system for actively damping boom noise as claimed in claim 47 wherein said acoustic wave sensor is configured to produce an acoustic wave sensor signal representative of said at least one tailgate vibration induced low-frequency acoustic mode.

59. A system for actively damping boom noise as claimed in claim 58 wherein said acoustic wave sensor signal comprises an electric signal indicative of measured acoustic resonance detected by said acoustic wave sensor within said enclosure.

60. A system for actively damping boom noise as claimed in claim 58 wherein said acoustic wave sensor signal is representative of a single tailgate vibration induced low-frequency acoustic mode.

61. A system for actively damping boom noise as claimed in claim 58 wherein said acoustic wave sensor signal is representative of a plurality of tailgate vibration induced low-frequency acoustic modes.

62. A system for actively damping boom noise as claimed in claim 50 wherein said acoustic damping controller defines a first electronic feedback loop input coupled to an acoustic wave sensor signal and a first electronic feedback loop output, wherein said first electronic feedback loop is configured to generate a first electronic feedback loop output signal by applying a feedback loop transfer function to said acoustic wave sensor signal.

63. A system for actively damping boom noise as claimed in claim 50 wherein said vibro-acoustic controller defines a second electronic feedback loop input coupled to a motion sensor signal and a second electronic feedback loop output, wherein said second electronic feedback loop is configured to generate a second electronic feedback loop output signal by applying a feedback loop transfer function to said motion sensor signal.

64. A system for actively damping boom noise comprising:

an enclosure defining a plurality of low-frequency acoustic modes, wherein said low-frequency acoustic modes are excited by idle engine firings;

an acoustic wave sensor;

a motion sensor secured to a panel of said enclosure;

an acoustic wave actuator substantially collocated with said acoustic wave sensor;

a first electronic feedback loop defining an acoustic damping controller; and

a second electronic feedback loop defining a vibro-acoustic controller.

65. A system for actively damping boom noise as claimed in claim 64 wherein said enclosure comprises a cabin of an automobile.